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"Empirical Studies of Solar Flares:
Comparison of X-Ray and H_α Filtergrams and
Analysis of the Energy Balance of the
Thermal X-Ray Plasma"

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I. INTRODUCTION

The general purpose of the research carried out under this contract was to investigate the physics of solar flares through combined analysis of X-ray filtergrams of the high-temperature coronal component of flares and H α filtergrams of the low-temperature chromospheric component. The specific observations studied were X-ray filtergrams from the American Science and Engineering (AS&E) X-ray telescope on Skylab and simultaneous H α filtergrams from Big Bear Solar Observatory (BBSO). These data were used for empirical studies of the following two topics.

1. The magnetic field configuration and its changes in flares.
2. The chromospheric location and structure of X-ray bright points (XBP) and XBP flares.

As will be reviewed below, significant results were obtained in both of these areas.

The X-ray and H α filtergrams, in combination with simultaneous X-ray spectral data, are also well suited for study of the energy balance of the thermal X-ray plasma in flares. The energy balance was not investigated during the contract period because the above studies seemed more fundamental (the magnetic field configuration and structure is a basic prerequisite for a realistic physical model for flares), and because our particular data sets had unique advantages for studies of geometry and structure. Moreover, because the above studies were so fruitful, they absorbed our full effort and forced the study of the energy balance to be neglected.

Nevertheless, our X-ray and H α data sets are still one of the best

sets of data in existence for analysis of the energy balance of the flare X-ray plasma. This underlines the fact that the potential of these data for probing the physics of flares is still far from exhausted.

III. RESULTS

A. The Magnetic Field Configuration and Its Changes in Flares

F. Tang and R. Moore carried out a complete search of the BBSO H α cine-filtergram films for coverage of X-ray flare events observed with the AS&E X-ray telescope on Skylab. S. Kahler provided lists of times and heliographic locations of all flare events (flares, active-region transients and non-active-region transients) detected on the AS&E X-ray filtergrams. A total of 64 X-ray events had at least some BBSO H α coverage: 44 flares, 16 active-region transients and 4 non-active-region transients. About half of these had reasonably good H α coverage of good quality and high resolution (≤ 1 arc sec): 15 flares, 11 active-region transients and 2 non-active-region transients.

Two of the above flare events were selected for detailed study of the magnetic field configuration and its changes in the flares. These were the 3B flare of July 29, 1973 and the active-region transient of August 29, 1973. These two flares were chosen for the following reasons.

1. Both flares had exceptionally good high-resolution H α coverage.
2. Both flares began with the eruption of a filament. In each case, the filament displayed the structure of the preflare

magnetic field over and along the magnetic inversion line where the flare started, and the H α movie of the eruption gave direct visual evidence of the nature of the change in the magnetic field during the flare.

3. Both flares were large enough in overall scale ($\sim 10^5$ km) so that both the H α structure and the X-ray structure were well resolved and the spatial relations between H α and X-ray structures could be determined.
4. For both events there was X-ray filtergram coverage before and after the filament eruption. For the August 29 flare there was good time coverage in X-ray pictures beginning during the filament eruption; this event had the best simultaneous H α and X-ray filtergram coverage of all large-scale flare events observed from Skylab. The July 29 flare was of particular interest because it was the largest H α flare observed from Skylab.
5. The July 29 flare and the August 29 flare together were of additional interest because they both occurred along the same magnetic inversion line on consecutive rotations.

R. Moore collaborated with S. Kahler and D. Webb of AS&E on the analysis of the August 29 flare and in writing a paper on this event. This paper, "X-Ray and H α Observations of a Filament-Disappearance Flare: An Empirical Analysis of the Magnetic Field Configuration", has been submitted to Solar Physics and will be presented by R. Moore at the January, 1980 meeting of the AAS (see appended abstract). The main point of this paper is that this flare was a four-ribbon flare which resulted from reconnection between two closed magnetic field systems. The observations of this event give perhaps the strongest

evidence to date that magnetic reconnection does in fact occur in at least some solar flares.

The analysis of the July 29 flare was carried out by R. Moore in collaboration with B. LaBonte of Hale Observatories. The results of this study are reported in their paper, "The Filament Eruption in the 3B Flare of July 29, 1973: Onset and Magnetic Field Configuration", which was presented by R. Moore at the IAU Symposium No. 91 and will be published in the Proceedings (see appended abstract). This paper presents the preflare magnetic field configuration inferred from the observations and points out that the filament eruption and the simultaneous onset of the H α flare were both probably triggered by reconnection between closed field lines below the filament.

Considering both the August 29 flare and the July 29 flare together, the main conclusions from our studies of the observations are the following.

1. The observations give compelling evidence that large-scale magnetic field reconnection operated throughout both flares. Since the two flares were very different, and since the July 29 flare was a classic example of a two-ribbon flare associated with a filament eruption, this implies that in a large class of flares the basic energy release is accomplished through large-scale reconnection as has long been proposed on theoretical grounds.
2. The initial reconnection was between closed field lines in both flares. This suggests that many (perhaps most) flares begin

as "four-ribbon" flares and evolve into bona-fide two-ribbon flares only if the overlying magnetic field is opened, as in a filament-ejection flare.

3. Neither flare was triggered by the emergence of new small-scale flux as proposed by Heyvaerts *et al.* (1977, *Astrophys.J.* 216, 123). This indicates that flares can be triggered by the same process that builds up the flare energy, i.e., by evolution of the overall magnetic field configuration.

B. The Chromospheric Location and Structure of XBP and XBP Flares

L. Golub of the Harvard-Smithsonian Center for Astrophysics provided lists of times and heliographic coordinates for a total of 95 XBP flares which had been identified from previous searches of the AS&E X-ray filtergrams. F. Tang and R. Moore exhaustively searched the BBSO H α films for coverage of these X-ray events.

The BBSO large-scale films cover about 1/20 of the solar disk (about the area of one large active region), and during Skylab these observations were usually centered on active regions. Consequently, very little coverage of quiet regions where XBP are not masked by strong overlying coronal X-ray emission was obtained on the large-scale films, and there was no large-scale H α coverage of any of the 95 XBP flares identified by Golub. The BBSO medium-scale films were also usually centered on active regions during Skylab, and although about 1/3 of the solar disk is viewed in these films, most of this area was usually in the latitude range of active regions, and the same masking effect by the overlying X-ray corona

strongly reduced the visibility of XBP and XBP flares in the observed areas. Consequently, it is not surprising that only one of the 95 XBP flares identified on the X-ray filtergrams had medium-scale H α coverage.

The search of the BBSO full-disk films for the H α signatures of the known XBP flares was more rewarding. We found that the XBP flares on the limb were quite readily detectable as H α macrospicules, but that the H α counterpart of an XBP flare on the disk was hardly ever identifiable on our full-disk films. Of the 95 XBP flares, there was simultaneous coverage on our full-disk films for 37, of which 10 were on or very near the limb and 27 were on the disk. We identified 9 of the 10 limb events with H α macrospicules, whereas we could identify only one of the 27 disk events. This one identified disk event was rather near the limb ($N50^\circ$, $W60^\circ$) and was noticed because it produced an obvious macrospicule. These results show that almost all XBP flare events powerful enough to be detected as XBP flares on the AS&E Skylab X-ray pictures produce H α macrospicules.

In addition to the list of known XBP flares, L. Golub provided a list of the times of all AS&E Skylab X-ray filtergrams which were optimally exposed (64 sec) and of optimum bandpass ($2-32 \text{ \AA}$ plus $44-54 \text{ \AA}$) for detection of XBP. The BBSO H α films were also exhaustively searched for coverage of ephemeral active regions (ER) and ER flares during these times. An XBP is the coronal component of an ER, and an H α ER flare is the H α counterpart of an XBP flare.

Several small candidate H α events for XBP flares were found on the large-scale H α films, but on checking with the X-ray filtergrams

it was found that these all occurred in obscured regions and/or were too weak in X-rays to be detected on the X-ray filtergrams. On the medium-scale H α films, we found 10 ephemeral region flare events with simultaneous X-ray coverage. Only one of these events appeared as an XBP flare on the X-ray filtergrams. These results indicate that flare activity in ephemeral active regions is more visible on high-resolution H α filtergrams than on the Skylab X-ray filtergrams, as was concluded from a previous study of H α flares in ephemeral regions (K.A. Marsh: 1978, Solar Phys. 59, 105).

On the medium-scale H α films, in addition to the 10 ephemeral region flare events with simultaneous X-ray coverage, we also found 10 H α events in XBP for which there was X-ray coverage within a few hours of the H α event. In several of these cases, there were several XBP in the field of view and several XBP pictures during the H α observing interval of 8-10 hr. On the large-scale H α films, we found one case of very good coverage of the birth of an XBP. These sequences were used to study the H α structure and relative H α and X-ray visibility of XBP on the disk.

As indicated above, using the BBSO full-disk H α films with the list of 95 known XBP flares, we found that nearly all XBP flares produce H α macrospicules. Going the other way - searching for XBP flares to go with known H α macrospicules - we identified a total of 42 H α macrospicules which were on the limb in our full-disk H α films at times of available AS&E Skylab X-ray pictures and which were identified without knowledge of whether or not there was an XBP

flare at that time. We then searched the X-ray pictures for X-ray signatures of the H α macrospicule events. The results are summarized in the following table.

| Coincident X-Ray Limb Event and/or Feature | Number of H α Macrospicule Events |
|--|--|
| Definite XBP flare | 7 |
| Possible XBP flare | 6 |
| XBP, but no change in brightness | 7 |
| No XBP | 6 |
| X-ray limb obscured | 16 |
| | <hr/> |
| | 42 |

These results indicate three things.

1. The large majority of all H α macrospicules are rooted in ephemeral active regions which are visible as XBP.
2. A reasonable fraction (~ 1/4) of H α macrospicules are rooted in XBP which are completely occulted by the limb.
3. A substantial fraction (1/4 to 1/2) of H α macrospicules are produced by microflare events which are too small and/or too weak in X-rays to appear as obvious XBP flares.

R. Moore and L. Golub plan to write two papers on the above results on XBP and XBP flares: one on the relation between H α macrospicules and XBP flares, and another on the H α appearance of XBP and XBP flares on the disk.

From our searches for ephemeral region flares on the disk, we learned to confidently identify ephemeral regions on our medium- and high-resolution H α films. They appear as tiny bipolar arch-filament systems and are usually clearly visible only when some flare-like activity is in progress. Thus they usually cannot be identified on a single H α frame, but are easily spotted when our films are projected as movies.

K. Marsh used this technique of identifying ephemeral active regions to interpret interferometric microwave maps of the quiet regions of the sun obtained with the Very Large Array (VLA) in New Mexico during a partial eclipse. He found that most of the bright peaks in the radio map coincide with ephemeral regions on our simultaneous H α pictures. He also used the observed X-ray and EUV properties of XBP to show that this result is reasonable in terms of the expected microwave emission from XBP. This work is reported in detail in a paper by K. Marsh, G. Hurford and H. Zirin "VLA Observations of Spatial Structure in the Quiet Sun at 6 cm During the October 1977 Eclipse", which has been accepted for publication in The Astrophysical Journal (see appended abstract).

III. CONCLUSION

The research supported by this contract has clarified the magnetic field configuration in filament-eruption flares and has revealed evidence for large-scale magnetic field reconnection in these flares. These results have been published in two papers.

We also empirically established the H α appearance of XBP and the relation between XBP flares and H α macrospicules. The H α signature of XBP has been used to interpret microwave maps of the quiet sun. This last work has been published, and it is planned that two other papers on the XBP and H α macrospicule results will be written and published. Finally, since the X-ray and H α data for Skylab flares is also well suited for studies of the energy balance of the thermal X-ray plasma in flares, we recommend further analysis of these data to investigate the energy balance. It is hoped that such additional studies will be carried out with support from other funding in the near future.

APPENDIX

Abstracts of Papers Published on Research Supported by This Contract:

"The Filament Eruption in the 3B Flare of July 29, 1973: Onset and Magnetic Field Configuration", R.L. Moore and B.J. LaBonte, Proc. of IAU Symp. 91, 1979.

"VLA Observations of Spatial Structure in the Quiet Sun at 6 cm, During the October 1977 Eclipse", K.A. Marsh, G.J. Hurford, H. Zirin, Astrophys. J. 1980, in press.

"X-Ray and H α Observations of a Filament-Disappearance Flare: An Empirical Analysis of the Magnetic Field Configuration", S.W. Kahler, D.F. Webb, R.L. Moore. Submitted to Solar Phys.

THE FILAMENT ERUPTION IN THE 3B FLARE OF JULY 29, 1973:
ONSET AND MAGNETIC FIELD CONFIGURATION

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High-resolution H α filtergrams prior, during and after the filament eruption are presented for this large, well-ordered, expanding two-ribbon flare. The implications of these observations, along with results from other studies of this flare in the Skylab Solar Workshop on Solar Flares, are discussed with regard to the preflare magnetic field configuration, the triggering of the flare and the destabilization of the filament, and the magnetic field configuration after the filament eruption. The observations show that:

1. The eruption of the filament and the onset of the two-ribbon H α flare were preceded by precursor activity in the form of small H α brightenings and mass motion along the neutral line and well below the bottom edge of the filament.
2. The filament erupted simultaneously with the precursor brightening of a small area that became part of one of the two H α flare ribbons which developed just after the filament erupted.
3. The distance of the H α ribbons from the neutral line was initially much less than the height of the filament above the chromosphere.
4. The precursor brightenings and the first brightenings in the flare ribbons were in the vicinity of the steepest magnetic field gradient in the flare region.
5. There was no evidence for emerging magnetic flux in the flare region.
6. Prior to the eruption, the filament was under an arcade of closed magnetic field lines.

From these results, we propose that:

1. The preflare magnetic field configuration was similar to that proposed by Heyvaerts et al. (1977, Astrophys. J. 216, 123), except that there was no emerging flux.
2. Both the destabilization of the filament and the initial flare ribbons resulted from magnetic field reconnection below the filament.
3. The reconnection began in the region of greatest shear in the magnetic field.
4. Following the initial reconnection which started the eruption, the filament eruption set up the magnetic field configuration for the two-ribbon flare in the manner proposed by Hirayama (1974, Solar Phys. 34, 323) and by Kopp and Pneuman (1976, Solar Phys. 50, 85), i.e., the filament eruption "opened" the overlying closed magnetic field lines, which then reclosed by reconnection in the wake of the expelled filament.

VLA OBSERVATIONS OF SPATIAL STRUCTURE
IN THE QUIET SUN AT 6 CM,
DURING THE OCTOBER 1977 ECLIPSE

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Observations of a quiet region on the solar disk were made during the partial solar eclipse of October 12, 1977 using the VLA at 4.9 GHz. Data from 21 baselines were used to make a series of one-dimensional synthesis maps as the moon de-occulted the field of view. Taking successive differences of the one-dimensional maps and applying a coordinate transformation yielded a two-dimensional map in which the basic resolution was $2''.5 \times 12''.7$. The map showed that the small-scale structure of the region was dominated by a small number of compact sources, whose mean angular size and peak brightness temperature were in the range $9''\text{--}25''$ and $(6\text{--}8) \times 10^4$ K respectively. Although comparison with high resolution H α photographs showed no clear correlation with the chromospheric network, at least 3 of 6 source positions were consistent with the locations of small bipolar regions. This raises the possibility that the radio sources are associated with X-ray bright points.

Theoretical considerations based on published EUV data show that the observed microwave structure cannot be explained by the normal chromospheric network. The available soft X-ray and EUV data are consistent, however, with the hypothesis that the microwave sources represent X-ray bright points.

X-RAY AND H_α OBSERVATIONS OF A FILAMENT-DISAPPEARANCE FLARE:
AN EMPIRICAL ANALYSIS OF THE MAGNETIC FIELD CONFIGURATION

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Observational results are presented for the magnetic field configuration and its change in a large-scale ($\sim 10^5$ km) subflare involving a filament disruption and disappearance which occurred on August 29, 1973. This event was well observed both in sequences of X-ray filtergrams from the AS&E experiment on Skylab and in an H_α filtergram movie from BBSO. These observations give evidence for both the preflare and postflare magnetic field configurations, from which we conclude that the flare was produced by large-scale reconnection between two closed bipolar field systems. This conclusion is based on the following specific observational results. (1) The flare was apparently a consequence of a new active region emerging and expanding into an old active region. The flare involved two magnetic inversion lines: one under the disrupted filament in the old active region and the other between the old region and the advancing new region. (2) The filament appeared to turn over and disappear in place without being ejected from the region. (3) The flare was a "4-ribbon" flare: each of the two inversion lines was straddled by a set of X-ray flare loops rooted in a conjugate pair of H_α flare ribbons. (4) The preflare structure of the flare region indicates that the old-region flux which is observed connected to the new region after the flare was connected across the old inversion line before the flare. The reconnection required to produce the observed postflare configuration from the probable preflare configuration would reduce the shear in the magnetic field across the old inversion line and could disrupt the filament without ejecting it.